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The Design and Analysis of Antiparallel Schottky Diode Mixers

Jeffrey Hesler

Abstract – **This paper discusses the techniques developed to design integrated anti-parallel Schottky diode mixers. The use of these techniques has enabled us to efficiently design and build submillimeter wavelength mixers that are not only highly sensitive, but also have enhanced mechanical robustness and large fixed tuned bandwidth. A "coaxial probe technique" is used with a finite-element analysis program to determine the loop and external embedding impedances of the anti-parallel diode pair. Nonlinear analysis of the diode is performed to examine such issues as mixer sensitivity and LO power requirement. As a design example, a 400 GHz subharmonic mixer with state-of-the-art performance is considered..**

I. Introduction

New techniques have been developed to scientifically design integrated planar Schottky diode mixers that are robust, easy to assemble, have large fixed tuned bandwidth and achieve state-of-the-art sensitivity. The diodes are integrated on a quartz circuit containing the embedding circuitry [1], which is placed in a microstrip channel. Two-sided waveguide-to-microstrip transitions are used to couple both the RF and LO signals into the channel. The integration of the diodes with the embedding circuitry allows precise control of the circuit geometry and a reduction of parasitic elements. Thus, diode integration allows greater accuracy of computer simulations and better sensitivity and bandwidth.

The primary focus of this paper is the method used to design integrated mixers, including both the embedding circuit design and the nonlinear analysis of the Schottky diode pair. The embedding circuit design includes the waveguide-to-microstrip transitions and the diode's embedding circuitry. The "coaxial probe technique" is used with HFSS to determine the loop and external embedding impedances. As a design example, a 400 GHz subharmonic mixer with state-of-the-art performance [2] will be considered.

II. Mixer Layout

The mixer block, similar to that described in [3], is split in the E-plane of the RF and LO waveguides, thus simplifying block fabrication and mixer assembly, as well as reducing the losses in the waveguides. The planar diode and mixer circuitry are fabricated on a 35 μm thick fused-quartz substrate. The circuits are then placed in a shielded microstrip channel which runs perpendicular to the RF and LO waveguides. A schematic of the mixer block circuit configuration is shown in Fig. 1. The diodes are located in the microstrip channel. Waveguide-to-microstrip transitions are used to couple both the RF and LO into the channel. The microstrip metallization bridges across each guide, necessitating the use of reduced height waveguide to achieve reasonable fixed-tuned bandwidths

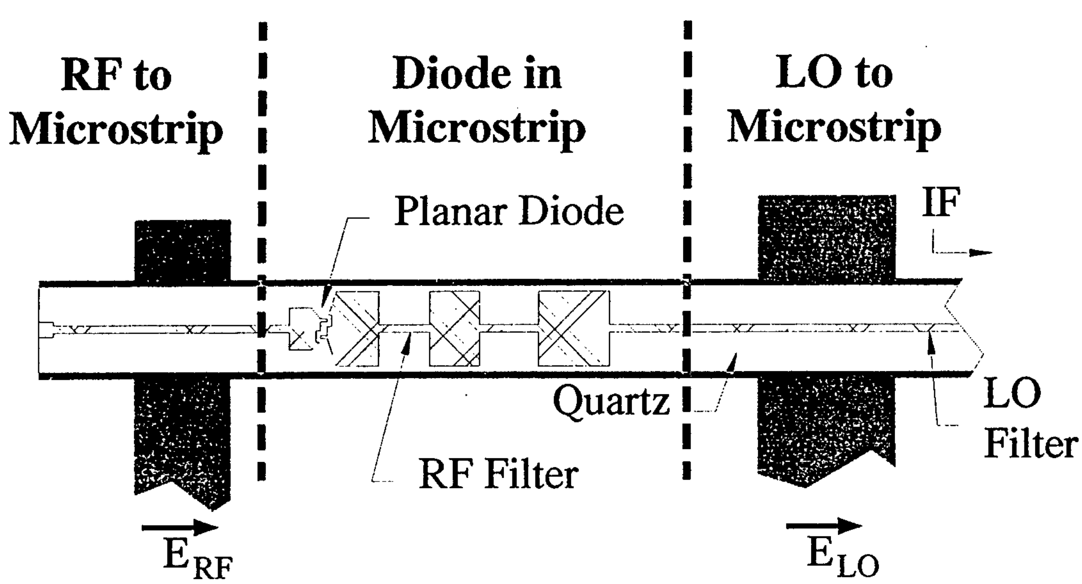

Fig. 1: Layout of the subharmonic mixer block configuration.

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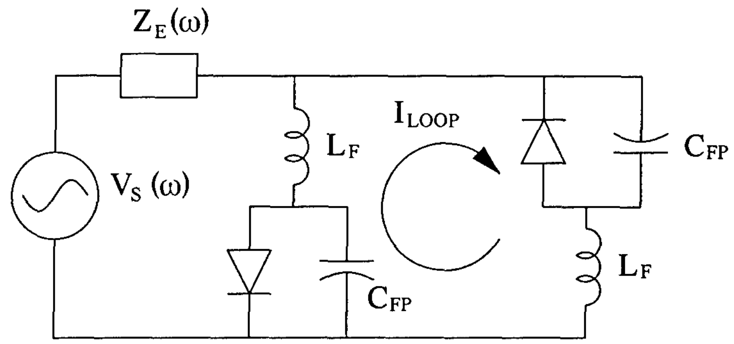


Fig. 2: Equivalent circuit of anti-parallel diodes used for the nonlinear analysis.

[4]. For this mixer, half height waveguide was used for the RF, and third height waveguide was used for the LO. A low-pass microstrip filter is used to prevent the RF signal from coupling to the LO guide, and a short-circuited half-wave stub is used to provide the LO termination.

III. NONLINEAR DESIGN

The equivalent circuit model of the anti-parallel diode used during the nonlinear design is shown in Fig. 2. The main goal of the nonlinear design is to determine the value of the external embedding impedance Z_E at the LO, RF and IF frequencies so that the external circuitry can then be tuned to present the proper impedance to the diode. In addition to this goal, the nonlinear analysis is used to look at mixer sensitivity and bandwidth, LO power requirements, and other performance issues.

In order to simulate the behavior of the nonlinear circuit it is first necessary to determine the reactance seen by loop currents. For the planar anti-parallel diodes used in this research the loop is well modelled by an inductance L_F (representing the diode finger and the lateral spacing between the diodes) and the junction fringing capacitance C_{FP} (the finger-to-pad capacitance). HFSS simulations of the anti-parallel diode mounted in a microstrip channel were performed to determine the appropriate values of L_F and C_{FP}. Coaxial ports were used at the anode junctions, as discussed in [5]. By feeding the two diode ports in phase (where this phase is referenced to the diode's polarity) we can then directly determine the loop reactance, from which we can calculate the loop inductance and capacitance. For a diode with a finger length of 20 μm and a lateral distance between fingers of 22 μm, L_F was 10 pH and C_{FP} was 2.5 fF. The same values of L_F and C_{FP} were found to match the HFSS simulations at both the LO and RF, thus giving an indication of the utility of the equivalent circuit used. In addition, L_F and C_{FP} were found to change very little when the external cavity was varied, and the same L_F and C_{FP} were found to be valid even when the diode was mounted directly in a waveguide.

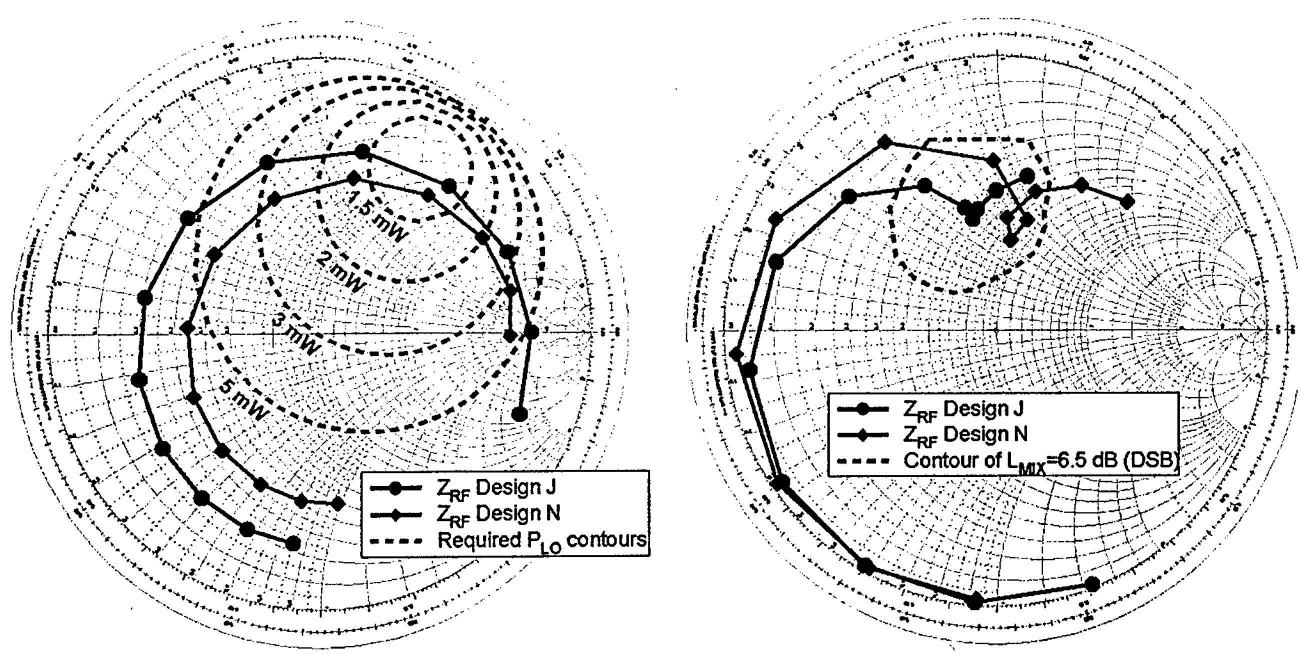
Using these values of the loop parasitics, nonlinear simulations were performed for an RF of 400 GHz. The Schottky diode that was modelled had an epitaxial layer doping of 4×10^{17} cm^{-3} and an anode diameter of 0.8-0.9 μm. The measured DC parameters for this diode were an ideality factor η=1.32, a saturation current $I_{SAT}=3\times10^{-13}$ A, and a series resistance R_S=10 Ω. The zero bias junction capacitance was calculated to be 1.5 fF per anode based on the anode diameter and the epitaxial layer doping. The simulations predict a mixer conversion loss of 4.0 dB (DSB) and noise temperature of 300 K (DSB) using 1.5 mW of LO power. The optimum embedding impedance Z_E was 30+j80Ω at the LO, 20+j30Ω at the RF and 100 Ω at the IF.

The total conductor and dielectric loss for the horn, waveguide, microstrip, and diode was estimated to be about 2 dB. Using this estimate the predicted performance is a mixer conversion loss of 6 dB (DSB) and mixer noise temperature of 650 K (DSB). The simulations predict a usable RF bandwidth of better than 20% fixed tuned.

The LO bandwidth is difficult to estimate since it is closely linked to the amount of power available from the LO source. In order to determine the effect of the LO embedding impedance on the mixer performance, a graph was made (see Fig. 3(a)) showing the required LO power as a function of LO impedance for the mixer simulated above. Fig. 3(a) was generated by realising that for a perfectly balanced subharmonic mixer the RF performance is unaffected by the LO embedding impedance as long as an equivalent amount of power is delivered to the diodes. Knowing this, we can then determine the amount of LO power required to keep the delivered power constant for a given LO embedding impdance. Fig. 3(a) shows that reasonably low LO power is required to drive the mixer over a large range of LO impedances.

IV. EMBEDDING CIRCUIT DESIGN

The LO and RF waveguide to microstrip transitions can be designed independently of the microstrip circuit around the diode. The transitions are designed to match the microstrip line to the waveguide, and can be therefore simply modelled during the microstrip circuit design. In order to achieve good fixed-tuned bandwidth the impedance of the microstrip lines running across the waveguide was set to about 100 Ω.



(a) **(b)**

Fig. 3: Predicted embedding impedance for two circuit designs at the LO and RF. (a) LO embedding impedance, with marker spacing of 6.7 GHz, (b) RF embedding impedance, with marker spacing of 13.4 GHz.

This impedance is a compromise between bandwidth, microstrip line loss, and the effect on the diode embedding impedance. A fixed-tuned bandwidth of approximately 20% was achieved for this design at the RF and LO. Wider bandwidths could be attained at the cost of some increase in circuit complexity.

The diode embedding impedance was found using the same method that was used to determine the loop parasitics. To determine the external embedding impedance Z_E rather than the loop impedance the diodes must be fed out of phase. The length of microstrip line between the RF waveguide and the diode can be used to tune the LO impedance while not affecting the RF impedance. The length of the first section of the RF-block filter is the primary tuning element for the RF circuit. Fig. 3 shows the predicted contours for two different mixer circuit designs as modelled in HFSS. The effects of the finite bandwidth of the waveguide-to-microstrip transitions has been included in the simulation. The fixed-tuned bandwidth of the RF is predicted to be about 20%.

V. Conclusions

This research has enabled us to efficiently design and build submillimeter wavelength mixers that are not only highly sensitive, but also have enhanced mechanical robustness and large fixed tuned bandwidth. The coupling of these new analysis techniques and the new integrated diode technology can be easily extended to other circuit designs such as balanced and subharmonic mixers and frequency multipliers, and will allow the development of a new generation of SubMillimeter-wave Integrated Circuits (SMICs) for a wide range of scientific, military and commercial applications

Acknowledgements

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